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The influence of depth of focus on visibility of monocular head-mounted display symbology in simulation and training applications

Marc D. Winterbottom
Air Force Research Laboratory
6030 South Kent, Mesa, AZ 85212

Robert Patterson
Washington State University
Pullman, Washington, 99164

Byron J. Pierce
Christine Covas
Air Force Research Laboratory
6030 South Kent, Mesa, AZ 85212

Jennifer Winner
Link Simulation and Training
6030 South Kent, Mesa, AZ 85212

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Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Readiness Research Division

NOTICES

//Signed// //Signed//

BYRON J. PIERCE
Project Scientist

HERBERT H. BELL
Technical Advisor

//Signed//

DANIEL R. WALKER, Colonel, USAF
Chief, Warfighter Readiness Research Division
Air Force Research Laboratory

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14. ABSTRACT
The Joint Helmet Mounted Cueing System (JHMCS) is being considered for integration into the F-15, F-16, and F-18 aircraft. If this integration occurs, similar monocular head-mounted displays (HMDs) will need to be integrated with existing out-the-window simulator systems for training purposes. One such system is the Mobile Modular Display for Advanced Research and Training (M2DART), which is constructed with flat-panel rear-projection screens around a nominal eye-point. Because the panels are flat, the distance from the eye point to the display screen varies depending upon the location on the screen to which the observer is directing fixation. Variation in focal distance may create visibility problems for either the HMD symbology or the out-the-window imagery presented on the simulator rear-projection display screen because observers may not be able to focus both sets of images simultaneously. The extent to which blurring occurs will depend upon the difference between the focal planes of the simulator display and HMD as well as the depth of focus of the observer. In our psychophysical study, we investigated whether significant blurring occurs as a result of such differences in focal distances and established an optimal focal distance for an HMD which would minimize blurring for a range of focal distances representative of the M2DART. Our data suggest that blurring of symbology due to differing focal planes is not a significant issue within the range of distances tested and that the optimal focal distance for an HMD is the optical midpoint between the near and far rear-projection screen distances

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The influence of depth of focus on visibility of monocular head-mounted display symbology in simulation and training applications

Marc D. Winterbottom[1], Robert Patterson[2], Byron J. Pierce[1,] Christine Covas[1,] Jennifer Winner[3]

[1] Air Force Research Laboratory, 6030 South Kent, Mesa, AZ 85212
[2] Washington State University, Pullman, WA 99164
[3]Link Simulation and Training, 6030 South Kent, Mesa, AZ

ABSTRACT

The Joint Helmet Mounted Cueing System (JHMCS) is being considered for integration into the F-15, F-16, and F-18 aircraft. If this integration occurs, similar monocular head-mounted displays (HMDs) will need to be integrated with existing out-the-window simulator systems for training purposes. One such system is the Mobile Modular Display for Advanced Research and Training (M2DART), which is constructed with flat-panel rear-projection screens around a nominal eye-point. Because the panels are flat, the distance from the eye point to the display screen varies depending upon the location on the screen to which the observer is directing fixation. Variation in focal distance may create visibility problems for either the HMD symbology or the out-the-window imagery presented on the simulator rear-projection display screen because observers may not be able to focus both sets of images simultaneously. The extent to which blurring occurs will depend upon the difference between the focal planes of the simulator display and HMD as well as the depth of focus of the observer. In our psychophysical study, we investigated whether significant blurring occurs as a result of such differences in focal distances and established an optimal focal distance for an HMD which would minimize blurring for a range of focal distances representative of the M2DART. Our data suggest that blurring of symbology due to differing focal planes is not a significant issue within the range of distances tested and that the optimal focal distance for an HMD is the optical midpoint between the near and far rear-projection screen distances.

Keywords: Head-mounted display, HMD, depth of focus, depth of field, accommodation

1. INTRODUCTION

The Joint Helmet Mounted Cueing System (JHMCS), a monocular head-mounted display (HMD), is currently being fielded in a variety of aircraft, including the F-15, F-16, and F-18. Similar HMDs are also being incorporated into the training systems for these aircraft. The JHMCS allows a pilot to track and designate targets for off-bore sight (OBS) targeting. In short, the pilot can shoot whatever he/she looks at. This capability allows the pilot to designate targets over a much wider field of view (limited only by the sensor capabilities of the missile targeting system). Currently, target designation can only occur within the limited field of view of the head-up display. OBS is therefore quite clearly a significant advantage in air-to-air engagements. In addition to OBS capability, the JHMCS also allows the pilot to designate ground targets, view symbology, such as attitude, altitude, air speed, etc. that would normally be presented on the head-up display, and obtain information regarding target locations from other aircraft via datalink.

The Air Force Research Laboratory, Mesa Research Site (AFRL, MRS) is considering integrating the JHMCS, or similar HMD, into the Mobile Modular Display for Advanced Research and Training (M2DART). The M2DART is a 360 degree field of view faceted display system used for DMO training and development at AFRL, Mesa.[1] This display system consists of eight flat display screens, with imagery rear-projected (see Fig. 1). Since it is a faceted display system, the distance from the eye-point to the display screen varies as the observer's head turns. When combined with a fixed focus distance monocular HMD this variation in focal distance may create visibility problems for either the HMD

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symbology or the out-the-window imagery presented on the simulator rear-projection display screen because observers may not be able to focus both sets of images simultaneously. The observer may perceive blurring of either the HMD imagery, the out-the-window imagery presented on the rear-projection M2DART screen, or both.

The extent to which blurring occurs will depend upon the depth of focus of the observers. If both the out-the-window display and the monocular HMD are within the observers' depth of focus, then no blurring will be perceived. However, if the separation between the two displays is large enough, observers may perceive significant blurring. In the M2DART, the variation between the focal planes of the two displays could be as much as 19 inches if the focus distance of the HMD imagery is set equal to that of the nearest distance between eye-point and display screen. A similar problem could be encountered with other faceted display systems, such as the Visual Integrated Display System (VIDS) available from Boeing Training and Support Systems (St. Louis, MO), the Simusphere available from Link Simulation and Training (Arlington, TX), or the Wide Angle Single eye Point (WASP) available from Glass Mountain Optics (Austin, TX). However, the variation in distance across the display facets will differ on each of these systems. The greater the distance between the HMD image plane and the simulated out-the-window image plane, the greater the potential for perceived blurring of the imagery. For a spherical dome type display this would not be an issue so long as the focal distance of the HMD is matched to the radius of the dome.

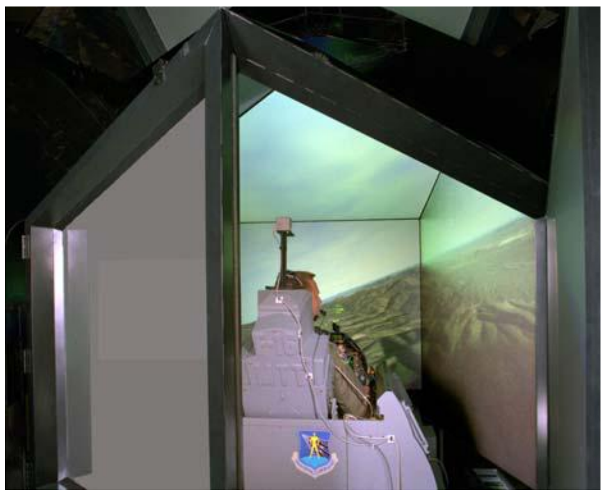

Figure 1. Air Force Research Laboratory M2DART.

Depth of focus refers to the range of distances in image space within which an image appears in sharp focus, and is specified in terms of diopters. An analogous spatial interval, given in meters, is referred to as depth of field.[2] Depth of field can be calculated using the formula $D = 1/F$, where D is the distance in meters, and F is distance in diopters. Objects varying in depth, such as variation in depth between the HMD and simulated OTW imagery, to an extent greater than a pilot or other observer's depth of focus will cause perceived blurring. Ogle & Schwarz[2] measured depth of focus for three observers using an apparatus which was configured to project a briefly presented target at varying distances. Observers attempted to identify the target while fixating on three Snellen acuity charts located 4 m in front of them. They found that total depth of focus was an average of 0.66 diopters under these conditions. Target size was also systematically varied using the apparatus described above and it was found that total depth of field increased by approximately 0.35 diopters per 0.25 arcminute increase in target size. For a two arcminute target, depth of focus was found to be approximately 2 diopters. Figure 2 below shows how depth of focus varies with target size under the conditions tested by Ogle & Schwartz[2]. Based on these results it is anticipated that depth of focus will not be an issue for visual displays with pixel sizes of 1.5 arcminutes or greater.

A psychophysical research study was undertaken to examine the role of depth of focus under conditions that simulated that of an M2DART integrated with a monocular HMD, such as the JHMCS. We employed a task similar to that of Ogle & Scwartz[2] described above but used viewing distances and luminance levels representative of those in the M2DART. Perceived blur was assessed by estimating the threshold size required for observers to identify the orientation of a block letter "E". Two experiments were performed. In Experiment 1 threshold size for accurate identification of orientation was estimated for conditions similar to those encountered in the M2DART with current rear-projection CRT display technology. In Experiment 2 threshold size for accurate identification was estimated for conditions similar to

that for an M2DART equipped with high resolution displays (i.e. 1 arcminute per pixel). In both experiments, we sought to determine whether the focus distance of the monocular display should be set to a distance matching that of the straight ahead view in the M2DART (36”), to a distance that matches the distance of the off-axis view (up to 55”), or to the optical midpoint of these two distances (43.5”).

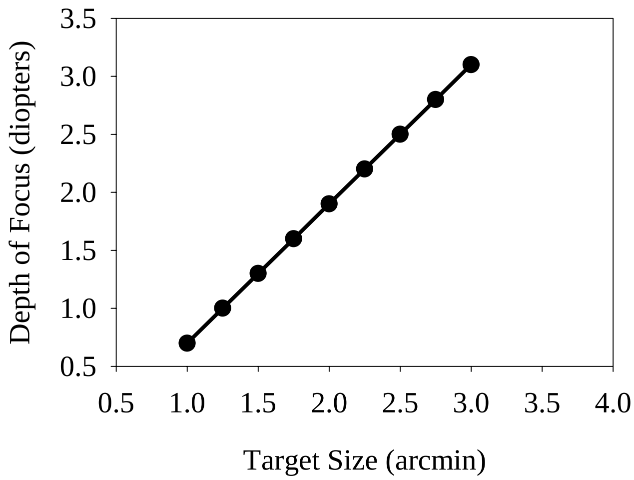

Figure 2. Increase in depth of focus as target size increases (based on Ogle & Schwartz, 1959)

2. EXPERIMENT 1

2.1. Methods

2.1.1. Observers

Five observers with normal or corrected to normal vision as determined by the acuity, binocular vision, color vision, and phoria measurement tasks of the Optec Vision Tester (Stereo Optical Co., Inc., Chicago, IL) participated.

2.1.2. Stimuli and Apparatus

Figure 3 shows the apparatus used for testing depth of focus for Experiments 1 and 2. A Barco 909 (Barco, Inc., Xenia, OH) CRT was used to rear-project a 52 x 43 inch image on to a 1.2 gain ProScreen (Proscreen Inc., Medford OR). The Barco 909 is similar to the CRT displays commonly used in the M2DART for DMO training and will be referred to as the binocular display. The binocular display was used to present a white background adapting luminance field, the fixation stimuli, and the front screen acuity test letter. The background luminance was set at 4 fL at the center of the rear-projection screen and is similar to the average luminance that would be encountered in the M2DART. The binocular display was capable of projecting approximately 1200 x 1100 resolvable lines based on the results of a standardized measurement procedure.[3,4] The fixation stimuli consisted of a series of five letters which were green in color (R, G, B values: 0, 255, 0). A green hue was chosen for similarity in appearance to the JHMCS symbology. The acuity test letter consisted of a block letter “E”, which was the same green color. The E was drawn on the screen such that the width and height were equal in number of pixels.

To simulate the monocular HMD, beam splitters were placed directly in front of the observer as shown in Figure 3. Two beam splitters were used so that there was not a significant difference in luminance across the two eyes. A VDC (VDC Display Systems, Cape Canaveral, FL) Sim 1600 LCoS projector was used to project a second acuity test letter E of the same green color to the right eye of the observer via the beam splitter. The projector was modified for a short focal length and rear-projected an image 5.5 x 4.4 inches in size onto a small DA-Lite DASS 50 screen (Da-Lite Screen Company, Warsaw, IN). The focus distance of the projector was modified so that the test letter was small enough to accurately measure observer acuity. With the modification, a pixel size of approximately 0.5 arcminute could be achieved. The Sim 1600 was capable of resolving approximately 1100 x 800 pixels under these conditions[3,4]. The combination of the LCoS display and beam splitters will be referred to simply as the monocular display. Neutral density

filters were used to reduce the luminance of the monocular display so that the black level did not exceed the background adapting luminance of the binocular display. A Shuttle PC equipped with a 3 GHz Pentium 4 processor and NVidia GeForce 4 videocard was used to generate the imagery and collect data. The videocard was configured to split a 2048 x 1024 image across two displays. Half the image was therefore displayed on the binocular display and the other half on the monocular display, each with 1280x1024 pixels.

A sliding platform, shown in Figure 3, allowed the distance between the monocular display and the binocular display and between the monocular display and the observer to be varied. The table at which the observers were seated could also be varied in distance from the binocular display. Observers were seated at a distance from the binocular display ranging from 28 inches to 96 inches. The distance of the monocular display from the observer varied between 36 and 55 inches. A chin rest was used to stabilize observer head position.

Figure 3. Depth of focus testing apparatus.

2.1.3. Procedure

At the beginning of each trial, a set of fixation letters were presented on the binocular display for a duration of 2 seconds. The fixation letters were approximately 50 arcminutes (0.83 degrees) in size and were scaled according to viewing distance so that retinal size remained constant. During this 2 second interval, observers indicated the identity of the centermost letter of the series, which served to ensure that the observer was accommodated to the distance of the binocular display. Following termination of the fixation letters, an inter-stimulus interval of 75 msec ensued, after which the target letter E was presented for a duration of 150 msec. The 150 msec duration is less than the latency of the observers' accommodative response[5] and was chosen to prevent observers from moving their accommodation away from the binocular display. The target letter E could be presented on either the binocular display or the monocular display. To further discourage observers from moving fixation away from the binocular display, the presentation of the E was weighted so that approximately 70% of the time it was presented on the binocular display. Observers indicated the orientation of the test letter E, either left or right, using a mouse. The test letter E was first presented at a large size, and then gradually decreased in size according to a staircase procedure. Two interleaved staircases were used to estimate a threshold size (the size of the gap in the E, or the smallest legible letter stroke width) for the test letter E presented on the binocular display. Two interleaved staircases were also used to estimate test letter E threshold size presented on the monocular display. Each observer repeated each set of trials twice, resulting in a total of 4 threshold estimates for each distance combination. The staircases converged on a threshold level of 70.7%[6].

2.2. Results

Figure 4 shows threshold size measured on the monocular display for different display separations (solid symbols). It can be seen that threshold size increased with the dioptric separation between the binocular and monocular displays. For comparison, the threshold size measurements obtained by Ogle & Schwartz[2] are shown as open symbols. An ANOVA indicated that display separation significantly affected threshold size [$F > 7.5$, $p < 0.01$].

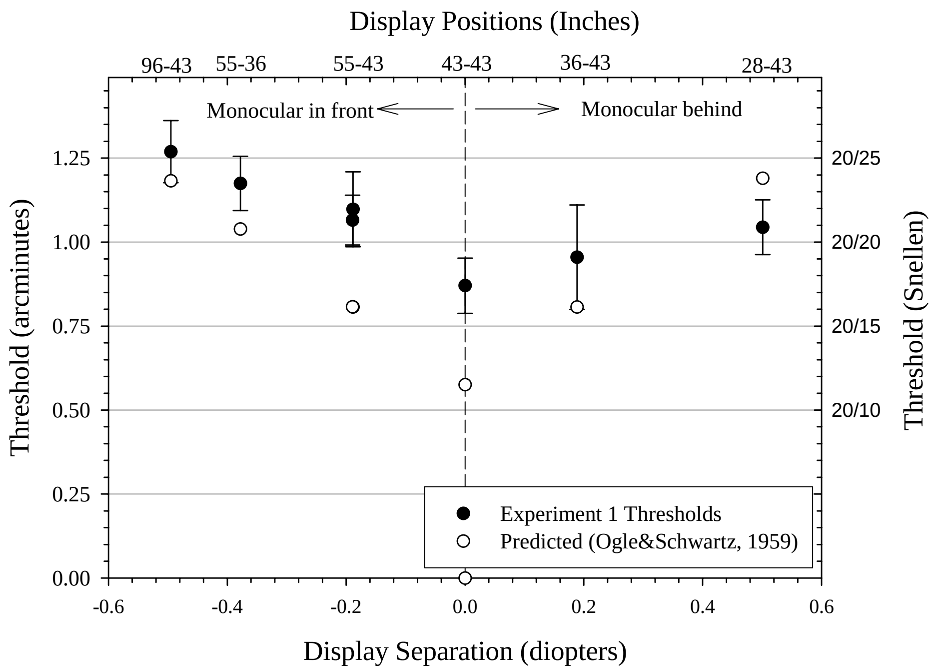

Figure 4. Experiment 1 monocular display thresholds.

2.3. Discussion

Based on the earlier work of Ogle & Schwartz[2], the threshold size for the high resolution target letter on the monocular display was expected to increase with display separation. Although threshold size did tend to increase with display separation, and was found to be significant, the results are not symmetric and were only roughly consistent with the results of Ogle and Swartz[2]. Nonetheless, it is apparent that depth of focus affected the visibility of targets presented on displays that varied in focal distance. For a criterion target size of 1 arcminute, depth of focus in Experiment 1 may be estimated to be approximately 0.4 diopters. Thus, for a monocular display set at a focal distance of 43.5 inches, which represents the optical midpoint, the nearest and farthest focal distances within the M2DART are within the observer's depth of focus. Note, however, that a monocular display set at a focal distance of 36 inches would fall outside the observer's depth of focus when fixation is directed to the M2DART.

A staircase procedure was also implemented for targets presented on the binocular display. However, the low resolution of the binocular display prevented the estimation of threshold in this case (targets were always large enough to be identified with 100% certainty). One main difference between our Experiment 1 and the study by Ogle & Schwartz[2] is that the low resolution of our binocular display may not have provided a strong stimulus for accommodation.

In Experiment 2, presented below, we sought to examine the effects on depth of focus for a higher resolution binocular-display, which provided a stronger stimulus for accommodation.

3. EXPERIMENT 2

3.1. Methods

3.1.1. Observers

Nine observers with normal or corrected to normal vision as determined by the acuity, binocular vision, color vision, and phoria measurement tasks of the Optec Vision Tester (Stereo Optical Co., Inc., Chicago, IL) participated.

3.1.2. Stimuli and apparatus

Stimuli and apparatus were identical to that of Experiment 1 except that an additional VDC Sim 1600 LCoS display was added to produce a high resolution inset on the binocular display. The image size and measured resolution

was similar to the LCoS described in Experiment 1. Neutral density filters were again used to reduce the luminance such that the black level did not exceed that of the background adapting level of the Barco 909. The Shuttle PC provided imagery to the two LCoS displays (one half of a 2048x1024 image on each as in Experiment 1). A second PC equipped with a 1 GHz Pentium 4 processor and NVidia GeForce 4 videocard was used to produce the white background imagery on the Barco 909.

3.1.3. Procedure

The procedure for Experiment 2 was similar to that of Experiment 1 with the exception that the fixation letters and front screen target letter E were presented using a second high resolution LCoS display. The size of the E could be reduced to approximately 2.5 arcminutes (0.5 arcminutes per pixel) when viewed at the nearest distance of 28 inches. The size of the fixation letters was approximately 7.5 arcminutes. The stroke width of the fixation letters was approximately 1.5 arcminutes. The retinal size of the fixation letters was again scaled for distance so that the size of the letters appeared constant regardless of viewing distance.

3.2. Results

Figure 5 shows threshold size measured on the monocular display for different display separations (solid symbols). It can be seen that threshold size tends to increase with greater optical separation between the monocular and binocular displays. Predicted threshold levels based on the results of Ogle & Schwartz[2] are again shown by the open symbols. A repeated measures ANOVA indicates that the effect of display separation was significant [$F > 10$, $p < 0.01$].

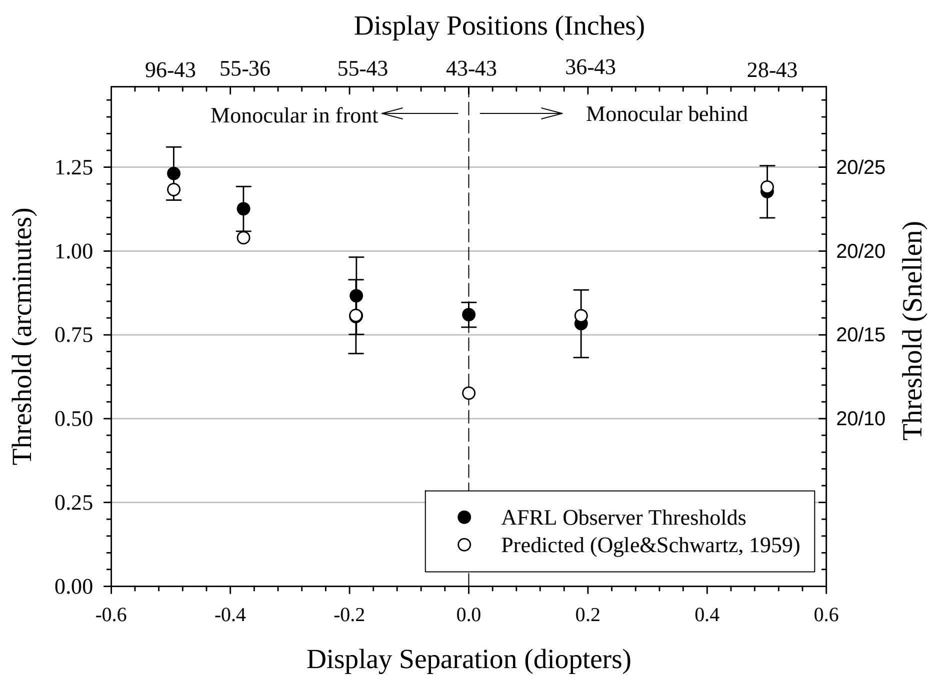

Figure 5. Experiment 2 monocular display thresholds.

Figure 6 shows the size thresholds measured for the binocular display in Experiment 2. Thresholds measured on the binocular display change very little across the separation distances tested, indicating that observers successfully maintained focus on the binocular display. An ANOVA indicated the existence of a significant interaction between display type (monocular vs. binocular) and display distance [$F = 5.0$, $p < 0.01$]. On average, thresholds were significantly greater when measured on the monocular display relative to those measured on the binocular display.

3.3. Discussion

The present results and those of Ogle & Schwartz[2] show remarkable agreement given that the testing conditions were quite different. Predicted thresholds based on Ogle & Schwartz[2] were nearly all within the sampling error of thresholds obtained in the present study. One exception is the separation distance of 0 diopters, where the threshold level measured for the monocular display did not continue to decrease to a level equal to that of the binocular display (Figure

6), or to a level predicted from Ogle and Swartz. Inspection of the target letter E stimuli presented on the monocular display device indicates that, after being attenuated by the beam splitter, the luminance of the target letter drops below that of the binocular display's background level of 4 fL (but only when the target letter E was reduced in size to a single pixel stroke width). This created an artificial elevation of measured threshold size. Based on the results shown in Figure 6, it can be argued that threshold level for targets presented on the monocular display would decrease to 0.6 arcminutes if the contrast level of the target letter were increased a small amount.

Based on the slope of the data shown in Figure 5, and for a criterion target size of 1 arcminute, depth of focus in Experiment 2 is estimated at approximately 0.64 diopters. Thus, for a monocular display set at a focus distance at the optical midpoint of 43.5 inches, the nearest and farthest focus distances of the M2DART are within this depth of focus. Similar to the results of Experiment 1, however, a monocular display set at a focus distance of 36 inches would fall outside this depth of focus under some viewing conditions in the M2DART.

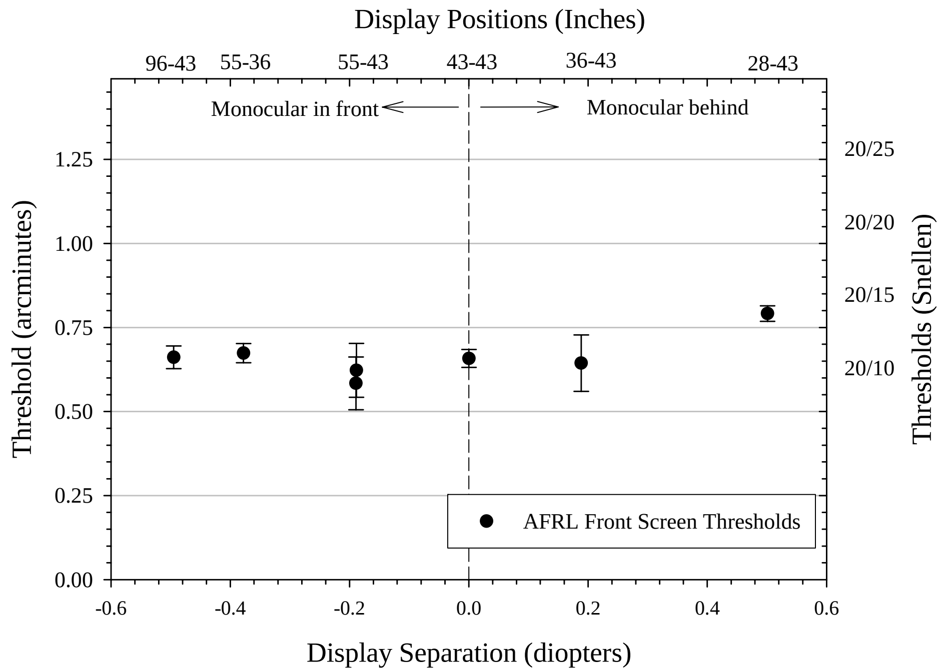

Figure 6. Experiment 2 binocular display thresholds.

4. CONCLUSIONS

In this study, we confirmed that depth of focus is not likely to be an issue for monocular HMDs worn while viewing faceted display systems equipped with standard CRT projectors. Standard CRT projectors, such as those installed in the M2DART, are limited to pixel sizes of approximately 4 arcminutes and the resolution of the JHMCS is at a comparable level. Figure 7 illustrates that the minimum target sizes of currently available systems are well above the level at which the effects of depth of focus are seen. At 3 arcminutes, the depth of focus reported by Ogle & Schwartz (1959) is greater than 2 diopters, more than enough for viewing JHMCS symbology and an M2DART simultaneously.

Our results also show that threshold size increases for very high resolution displays. Yet even in the case where a monocular HMD, such as the JHMCS, is integrated with a binocular display of very high resolution (e.g., 1 arcminute/pixel) it is unlikely that blurring of HMD symbology would be evident to the observer. Even though the depth of field around the fixation point of the high resolution display would be reduced, as shown by the results of Experiments 1 and 2, the depth of field for targets on the HMD would remain large so long as the HMD resolution remains relatively low. Symbology on a low-resolution HMD should remain visible even with modest differences in focal length between displays. However, some blurring of detail could be evident in the high-resolution binocular display if fixation of the observer was drawn to the HMD. For example, if the HMD focal length were set to 36" and the observer were focused at that distance while simultaneously trying to view a small target (such as a distant simulated aircraft) on the binocular

display at the farthest distance of 55” (an optical separation of 0.39 diopters), the resolvable detail on the binocular display would decrease.

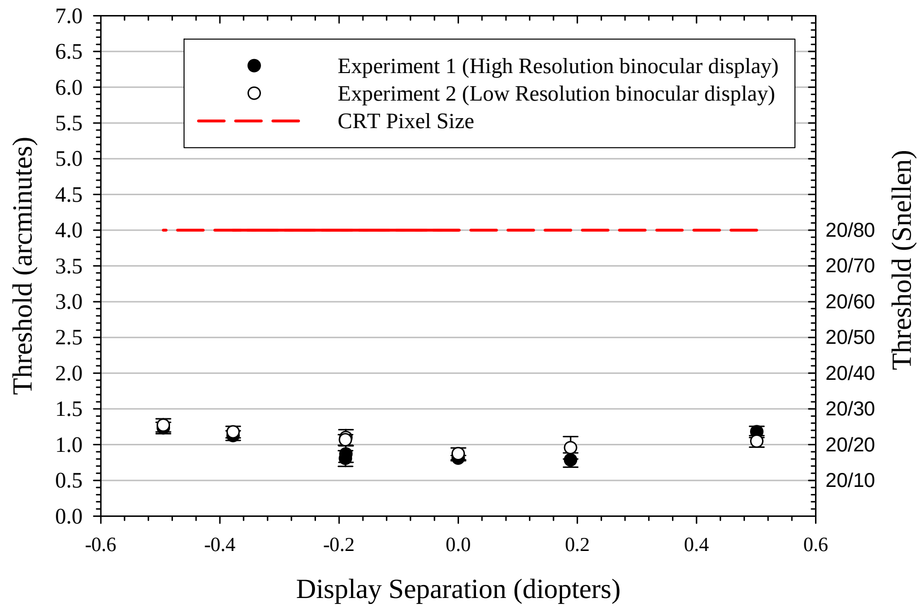

Figure 7. Threshold levels of Experiments 1 & 2 compared to resolution of currently available display systems.

In order to reduce this possibility, or in the event that a very high-resolution monocular HMD is integrated with a high-resolution binocular display, it is recommended that the HMD focus distance be set to the optical midpoint of the nearest and furthest focal planes expected for the binocular display. The optical midpoint is calculated by averaging the dioptric distances of the nearest and farthest focal planes of the background display. For the M2DART, the nearest viewing distance is 36” (0.91 m) and the farthest viewing distance is 55” (1.4 m). The following equations were used to compute the optical (O_m) and spatial (S_m) midpoints for the M2DART:

$$Om = ((1/0.91m) + (1/1.4\,m))/2 = 0.9\,diopters$$

$$Sm = 1/0.9\,diopters = 1.1m = 43.5\,inches$$

Setting the HMD focus distance to this intermediate value reduces the maximum dioptric separation possible in the M2DART from 0.39 diopters to 0.19 diopters and significantly reduces any blurring that might be present for small targets on a high resolution display.

In the present study, we found that the symbology on the monocular display, as well as the imagery on the binocular display, appeared in sharp focus and without blurring under conditions that simulated the wearing of an HMD within the current configuration of the M2DART. However, there are two other issues that should be addressed in the future with respect to depth of focus in training applications, namely, luminance level and eye strain/visual discomfort.

A reduced luminance level, which increases pupil diameter, can be expected to reduce an observer's depth of focus to a degree greater than that observed in the present study. Thus, the degree to which low luminance levels produce a blurring of targets should be examined under conditions that simulate the M2DART. Moreover, the conditions employed in the present study were carefully designed to minimize steady-state changes in accommodation (e.g., brief target presentations), which, in turn, should have led to little or no eye strain or visual discomfort. It is possible, however, that continuous adjustments of accommodation for targets presented at differing distances could be uncomfortable for observers. Shibata[7], for example, found that observer ratings of eyestrain increased when vergence angle was mismatched for accommodation when a binocular HMD was used. Hakkinen[8] also found that ratings of

eyestrain were significantly higher when viewing a monocular HMD compared to a standard CRT monitor. Similar issues would likely arise when a monocular HMD is combined with a binocularly-viewed faceted display, such as the arrangement used in the present study. The occurrence of eyestrain/visual discomfort should be examined to ensure that the integration of monocular HMDs into faceted binocular display systems, such as the M2DART, is appropriate, particularly under conditions of extended use where the observer may be continually adjusting accommodation between two displays differing in focal distance.

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